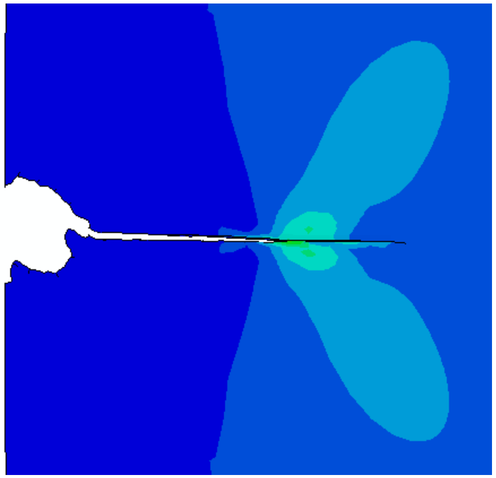
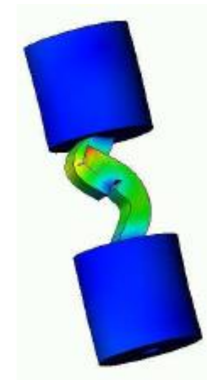
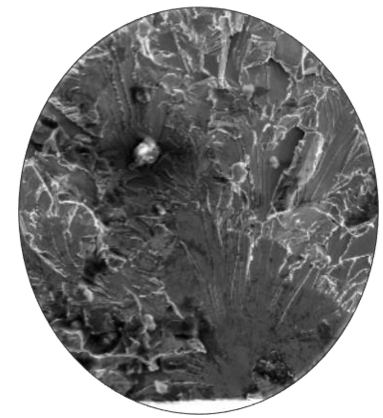
Exceptional service in the national interest



N-O-MAD





Project 4: Fatigue Behavior of Fe-Co-2V using Experimental, Computational, and Analytical Techniques

Students: Jacob Biddlecom, Benedict Pineyro, Matthew Mills

Mentors: Kyle Johnson, Scott Grutzik, Tariq Khraishi, Adam Brink, Matthew Brake

July 31, 2018

THE UNIVERSITY of NEW MEXICO

Sandia National Laboratories

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SAND2018-8328 C

Mentors

Kyle Johnson (SNL)

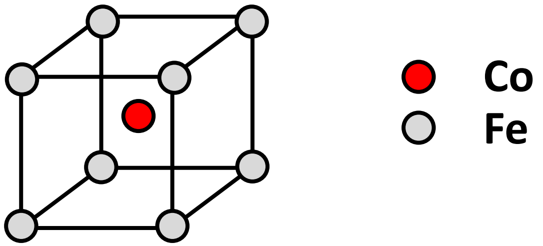
Scott Grutzik (SNL)

Adam Brink (SNL)

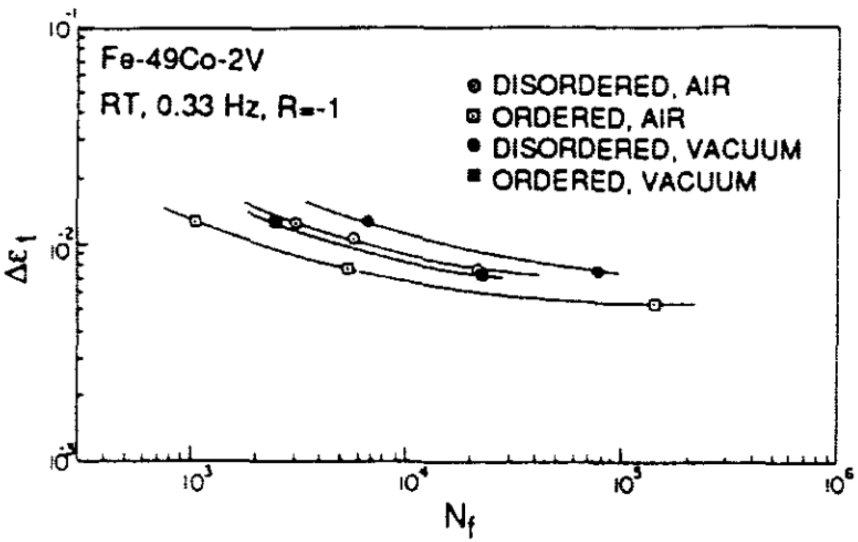
Matthew Brake (Rice University)

Tariq Khraishi (UNM)

Motivation



- Fe-Co-2V is soft, ferromagnetic material commonly used for electrical components
- Often exhibits low strength, poor ductility, and low workability due to an ordered B2 microstructure
- Limited fatigue data currently exists for Fe-Co-2V



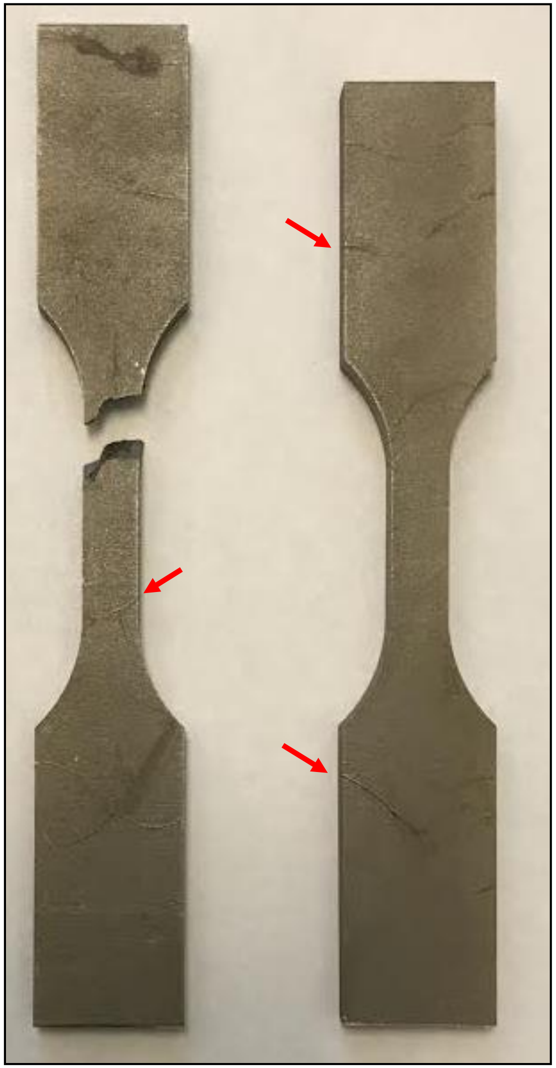
[Source: Stoloff et al., Scripta Metallurgica et Materialia, 1992]

Project Goal

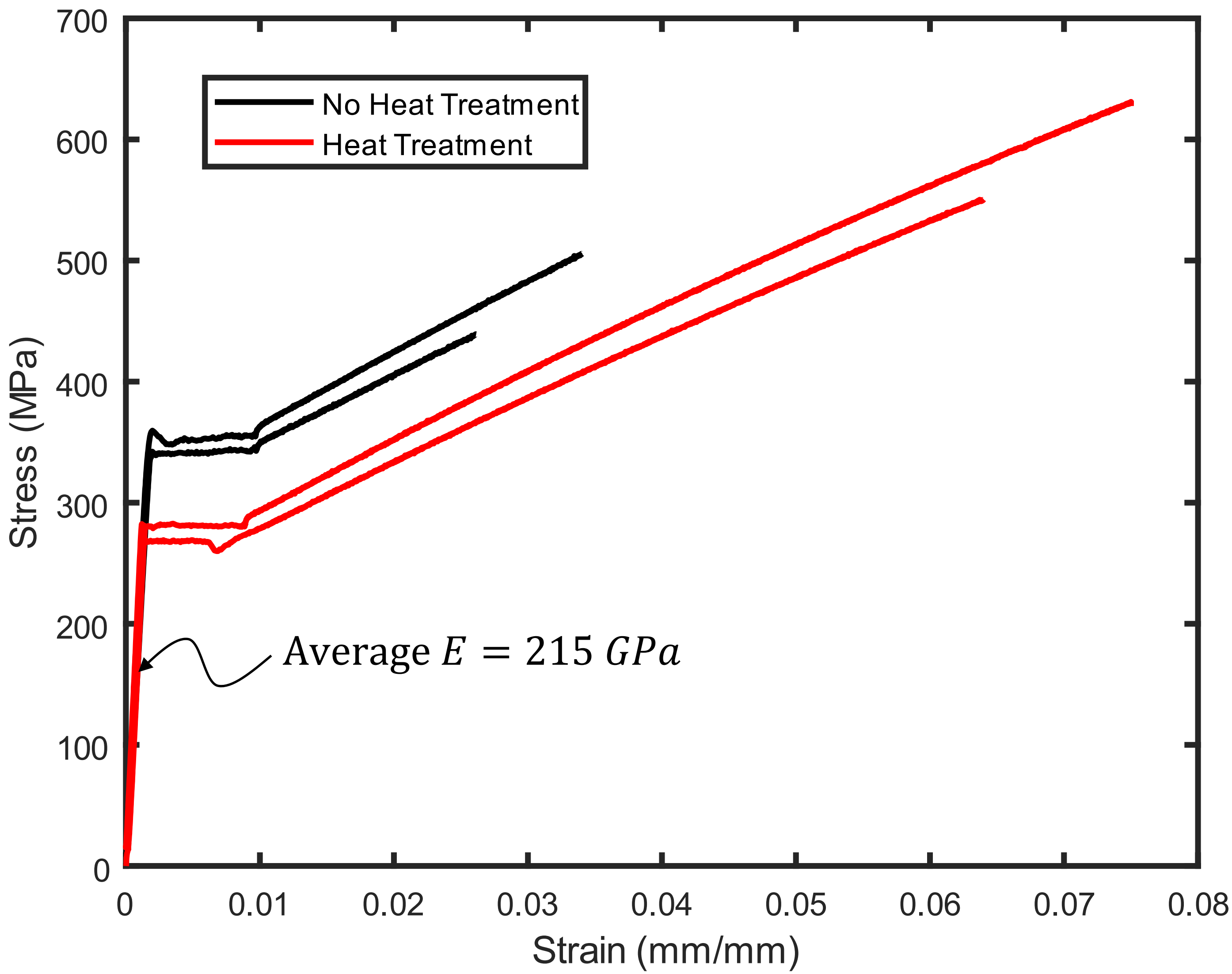
Characterize the fatigue properties of Fe-Co-2V through strain-controlled fatigue testing coupled with numerical and analytical modeling

Additively Manufactured (AM) Fe-Co-2V

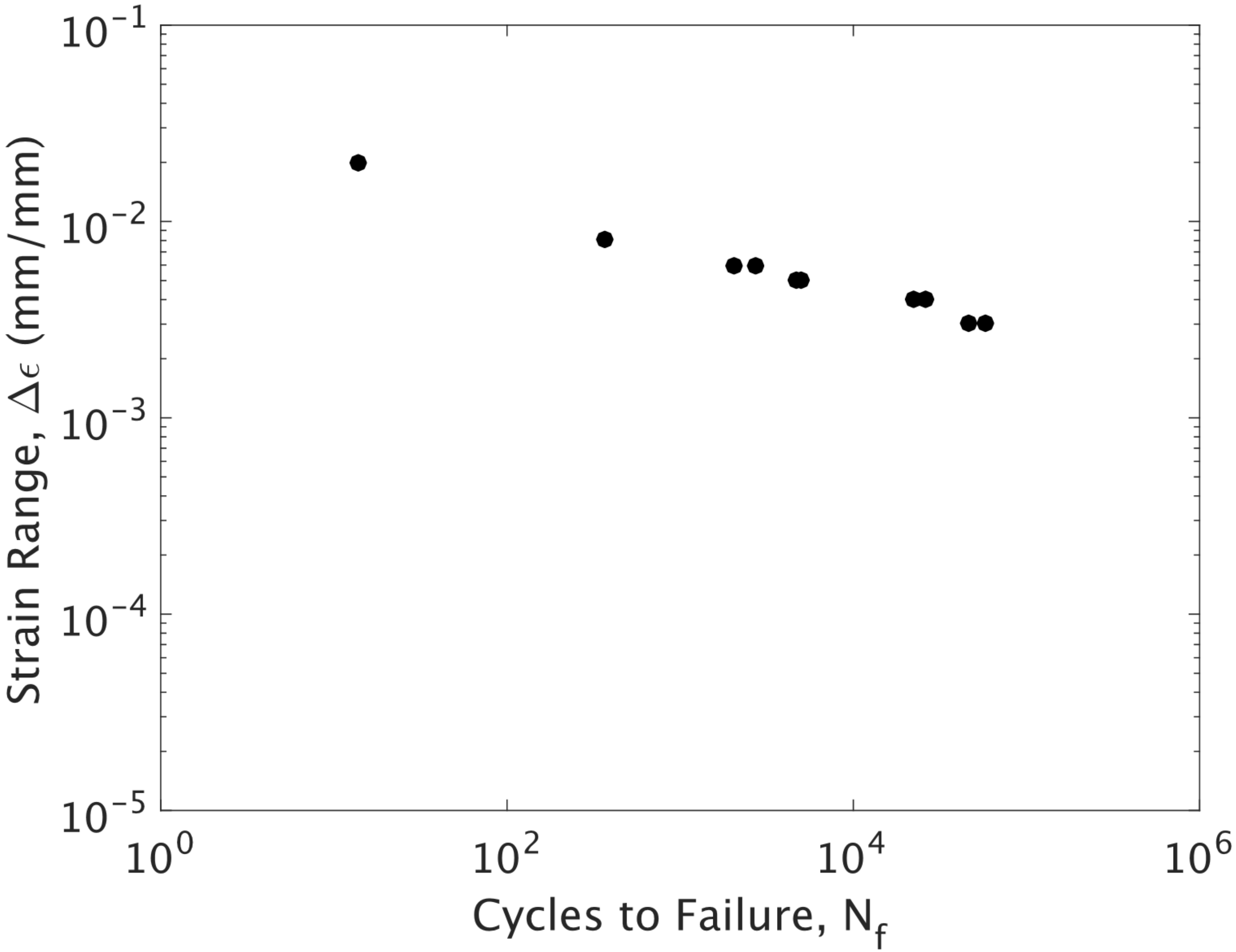
- Producing Fe-Co-2V using AM could potentially improve its mechanical properties
- AM Specimens exhibited significant cracking, likely from thermal residual stresses
- Proceeded to use wrought Fe-Co-2V for the study



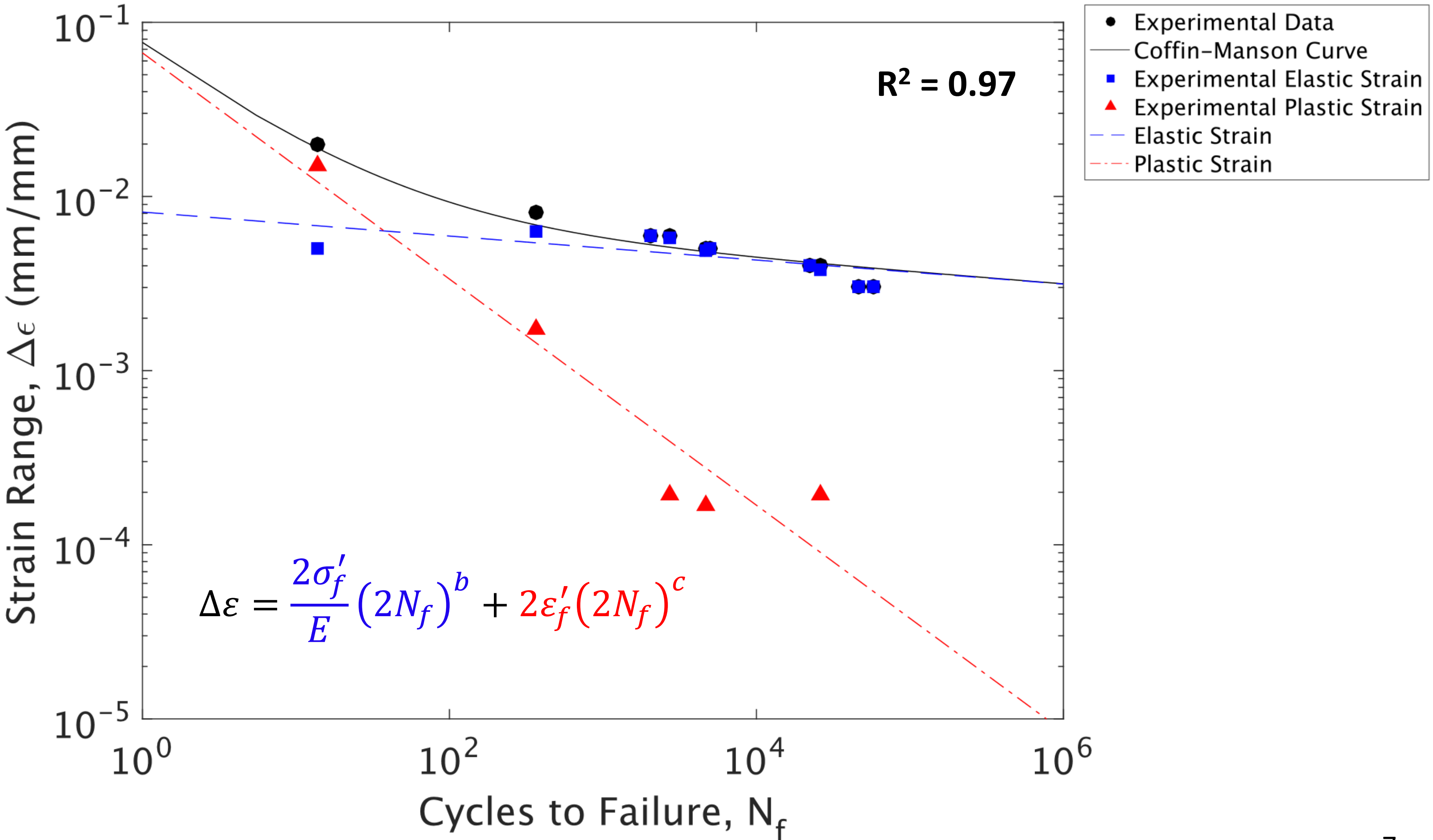
Quasi-Static, Monotonic Tension Tests



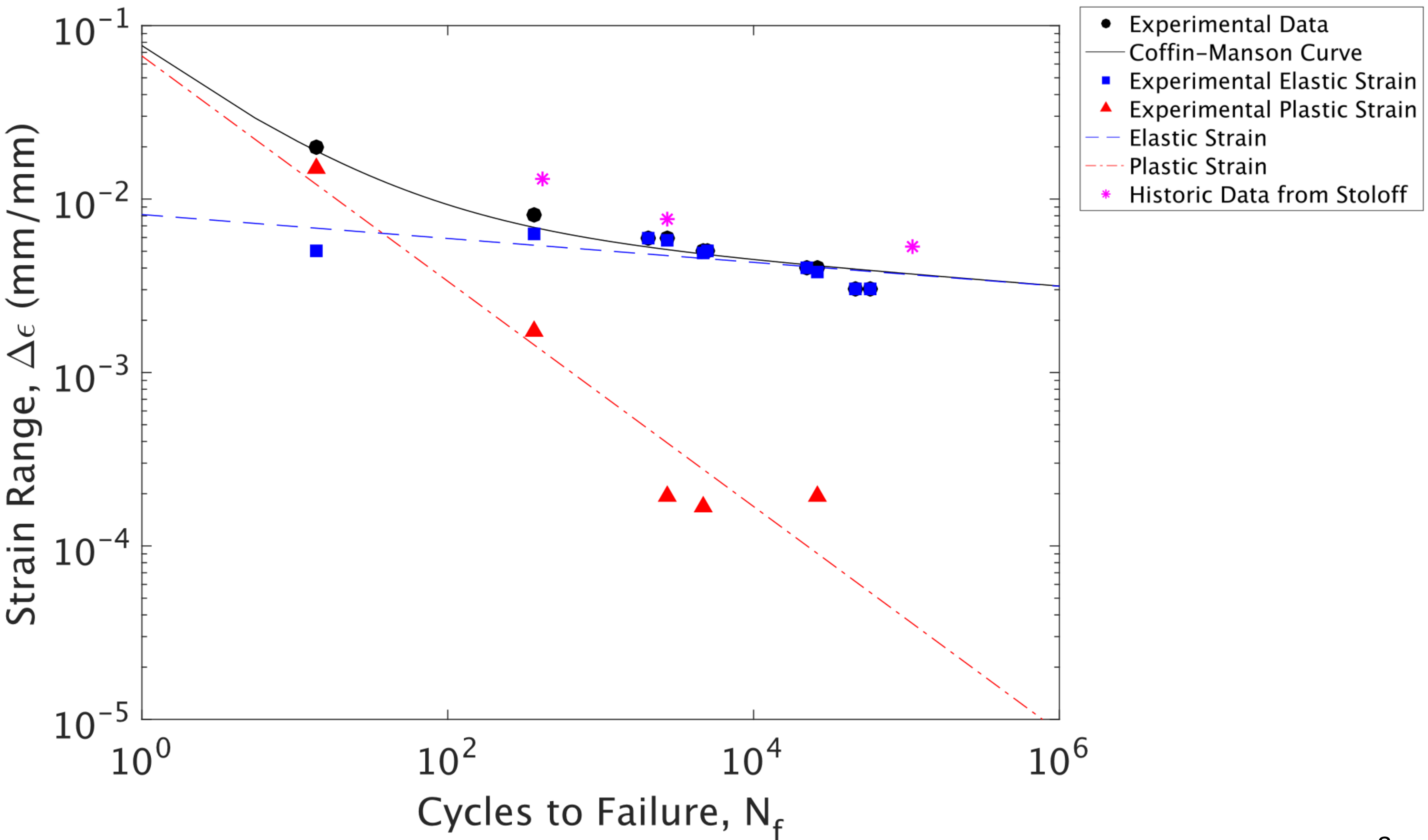
Strain-Controlled Fatigue Testing (R=-1, 1 Hz)



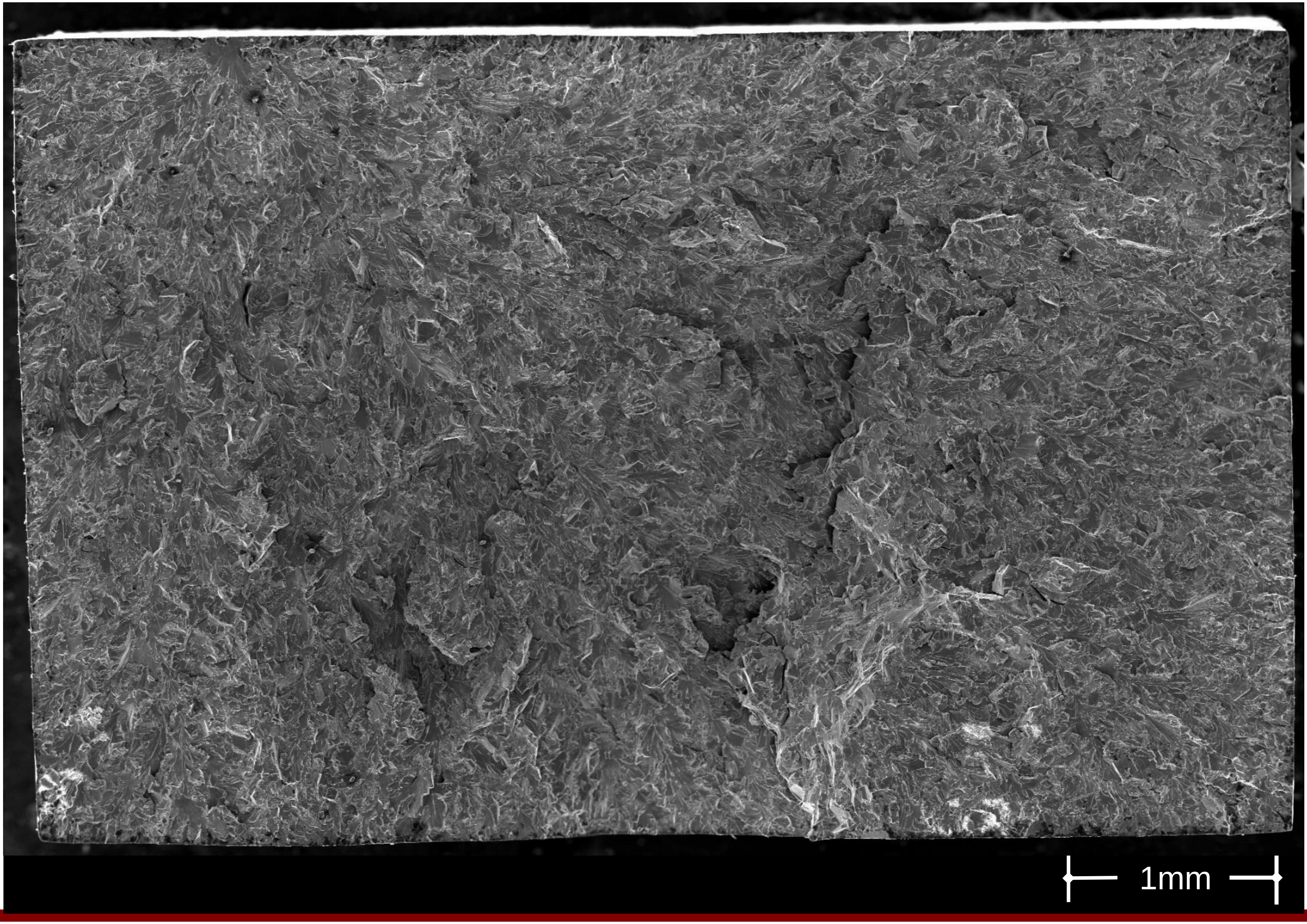
Strain-Controlled Fatigue Testing (R=-1, 1 Hz)



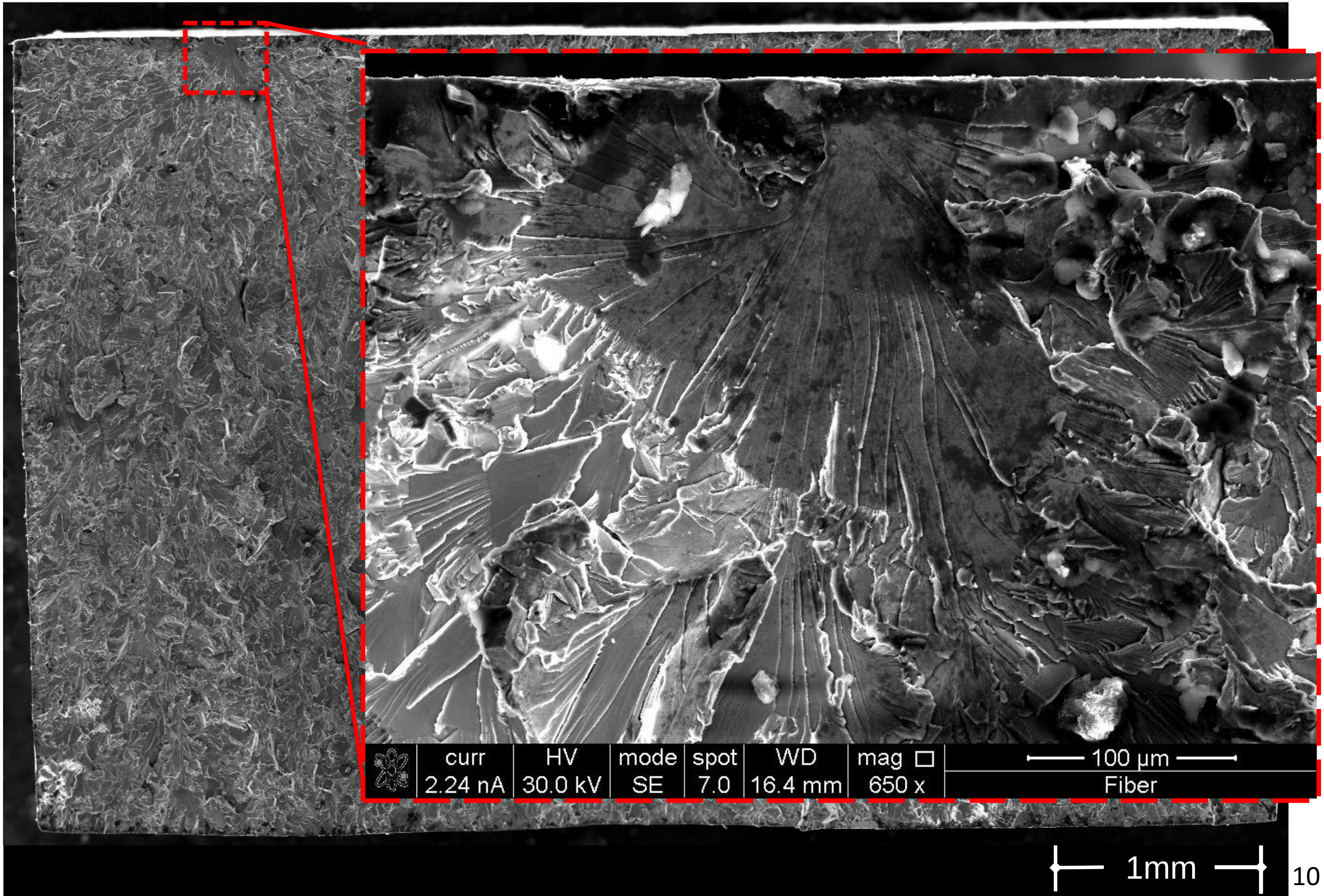
Strain-Controlled Fatigue Testing (R=-1, 1 Hz)



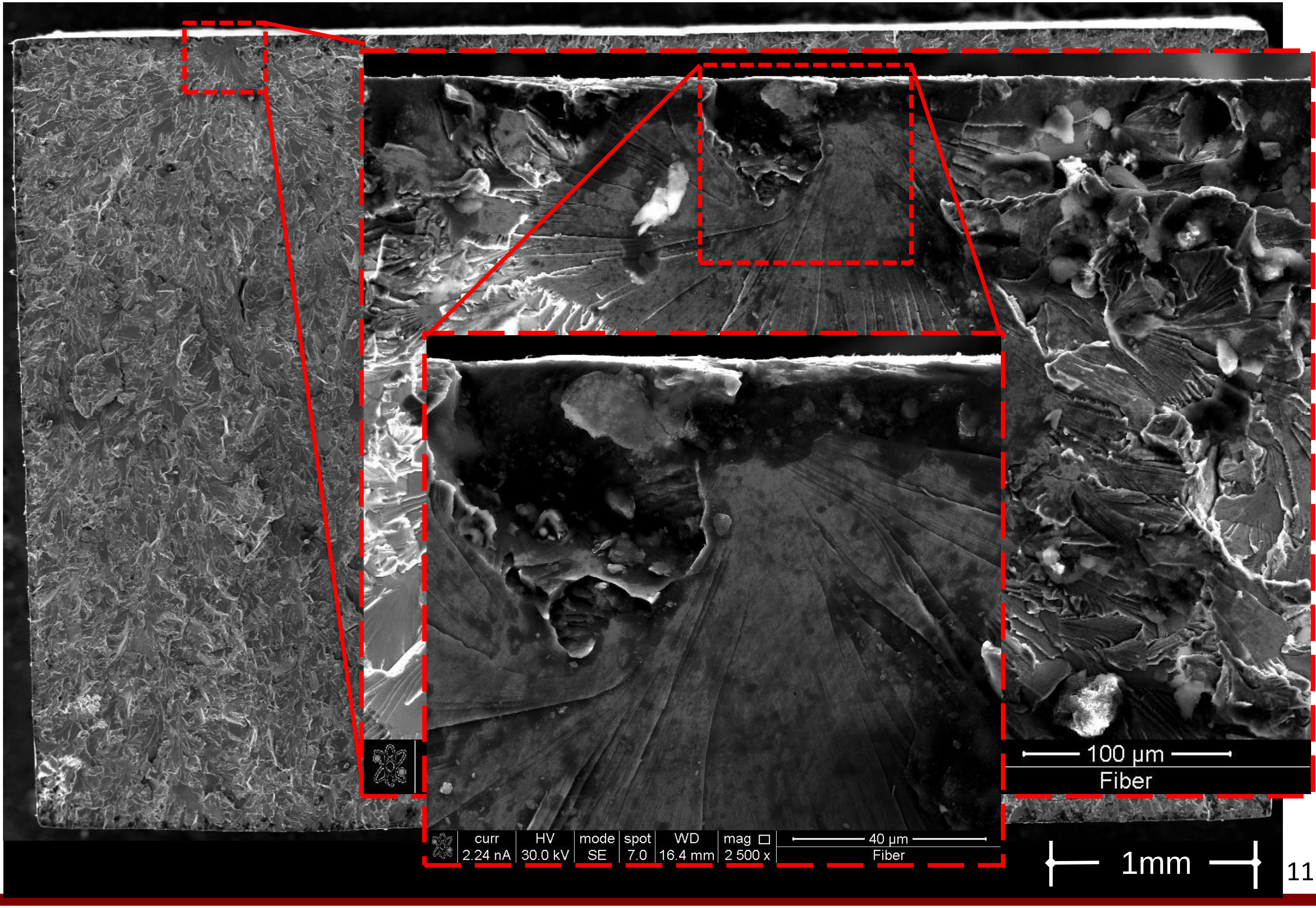
SEM – 1mm Scale



SEM – 100µm Scale

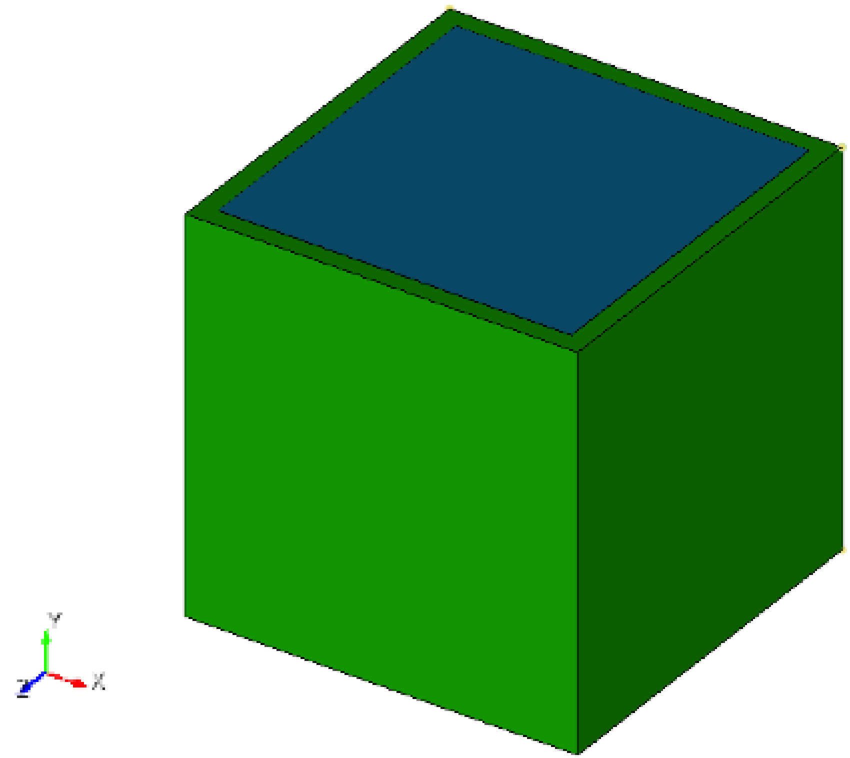


SEM – 40μm Scale



Calibration – Methods

- Gradient
  - Sequential Least Squared Programming (SLQSP)
  - Nelder-Mead
- Global
  - brute
  - basinhopping



Error Metric:

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=0}^{n} |f_i - y_i|^2$$

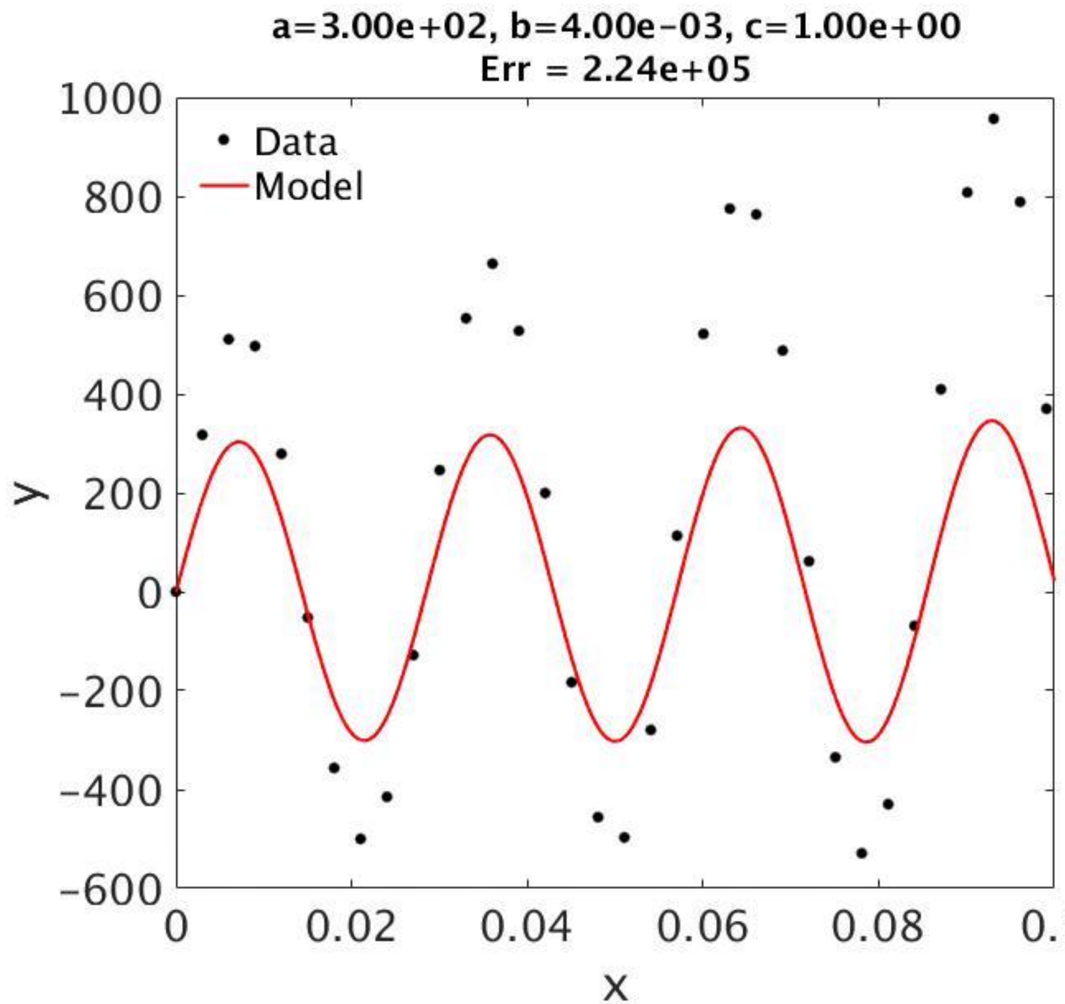
- Weighted function

Calibration – Methods

Gradient

- Fast Convergence
- Susceptible to local minima vs. global

Global



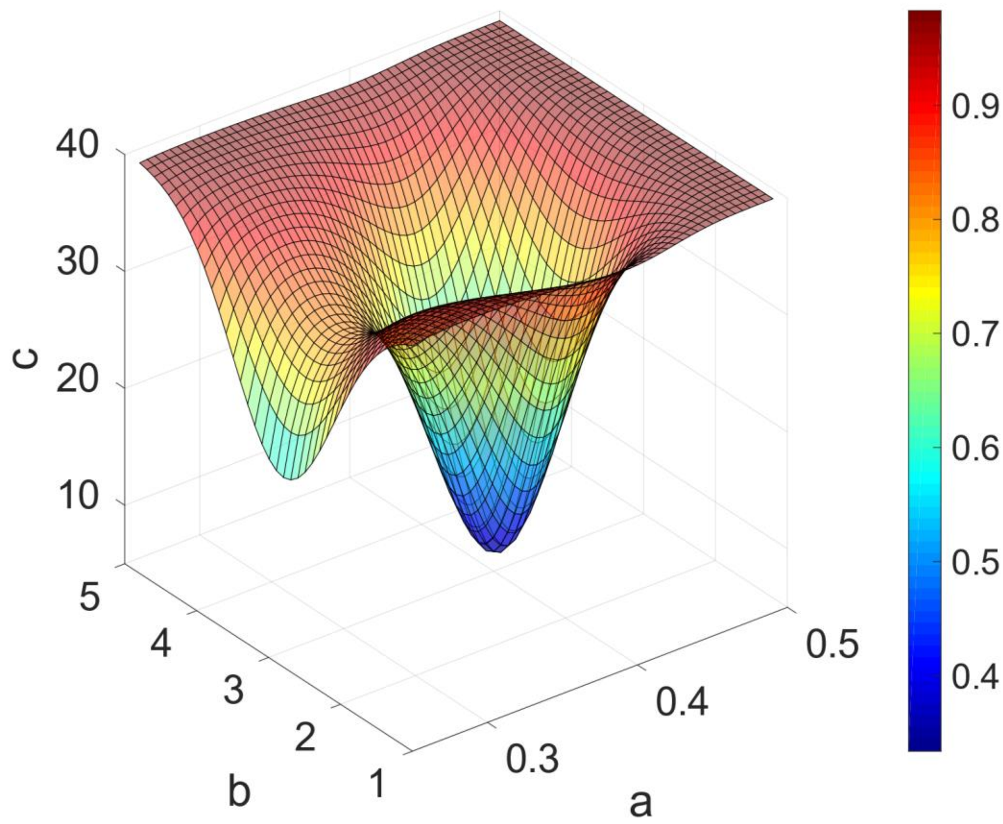
$$y = a \cdot \sin(x) \cdot \exp(bx) + cx$$

Calibration – Methods

Gradient

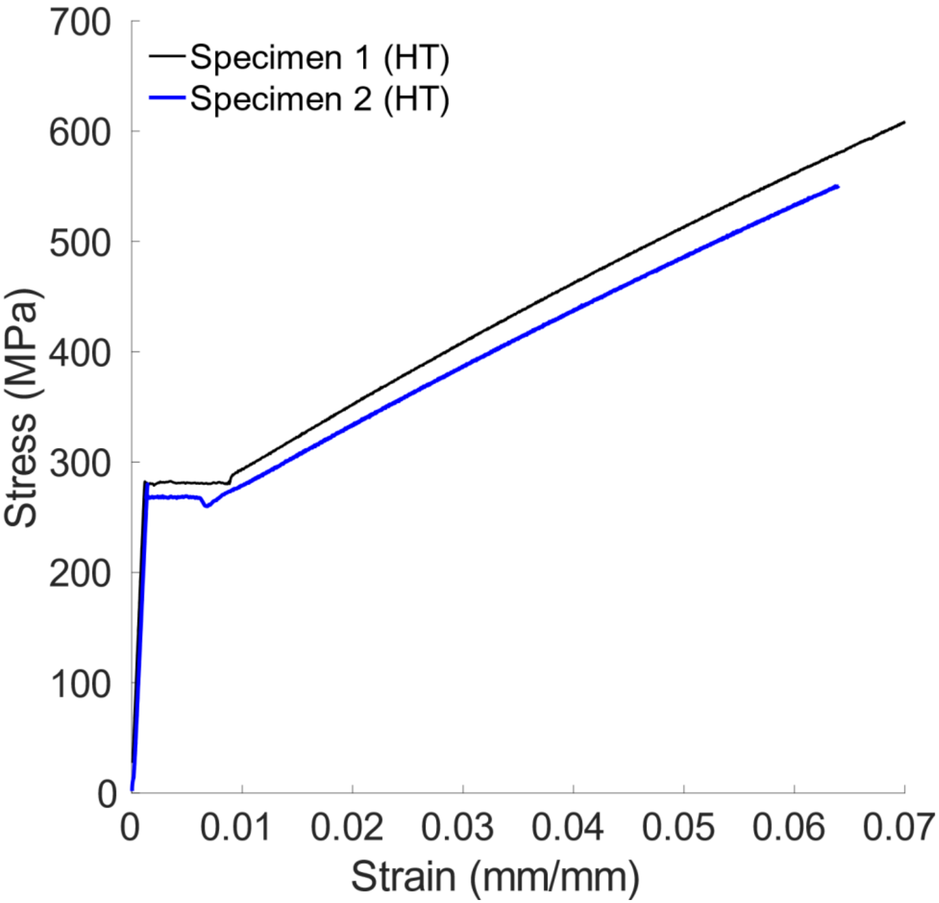
Global

- Guarantees minima
- Inefficient, can run into memory problems

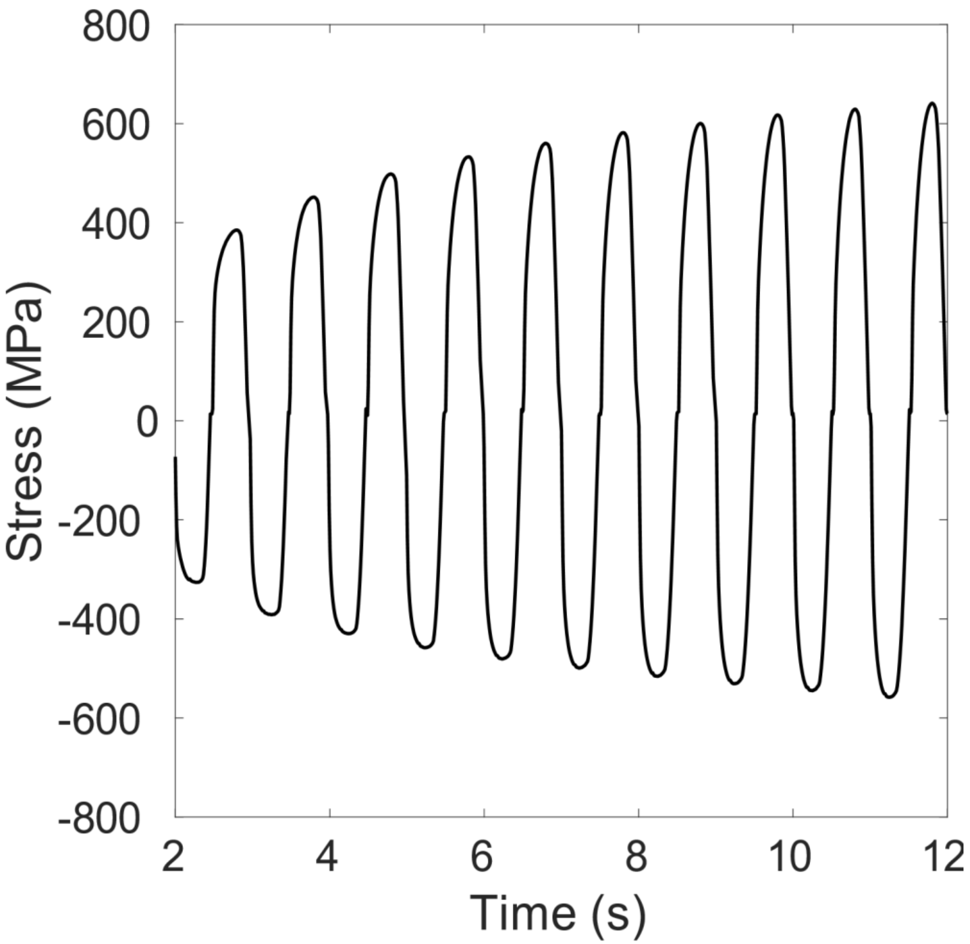


Error Function

Calibration – Data



Monotonic



Cyclic

Monotonic Calibration

J_2 Plasticity

- Generic Implementation of a von Mises yield surface with kinematic and isotropic hardening features

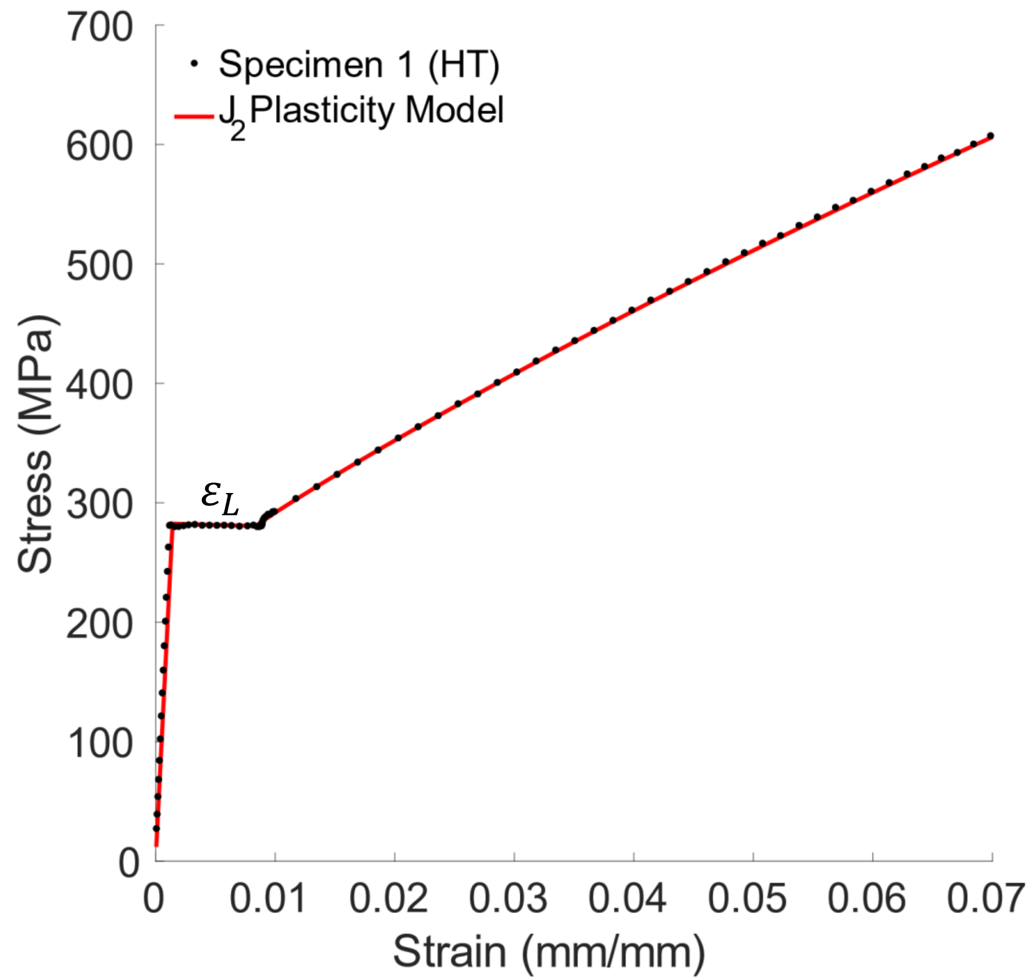
Power Law

- Describes isotropic hardening of the material

$$\bar{\sigma} = \sigma_y + A\langle \bar{\varepsilon}^p - \varepsilon_L \rangle^n$$

Parameters

$$E, \sigma_y, \varepsilon_L, \nu, n, A$$



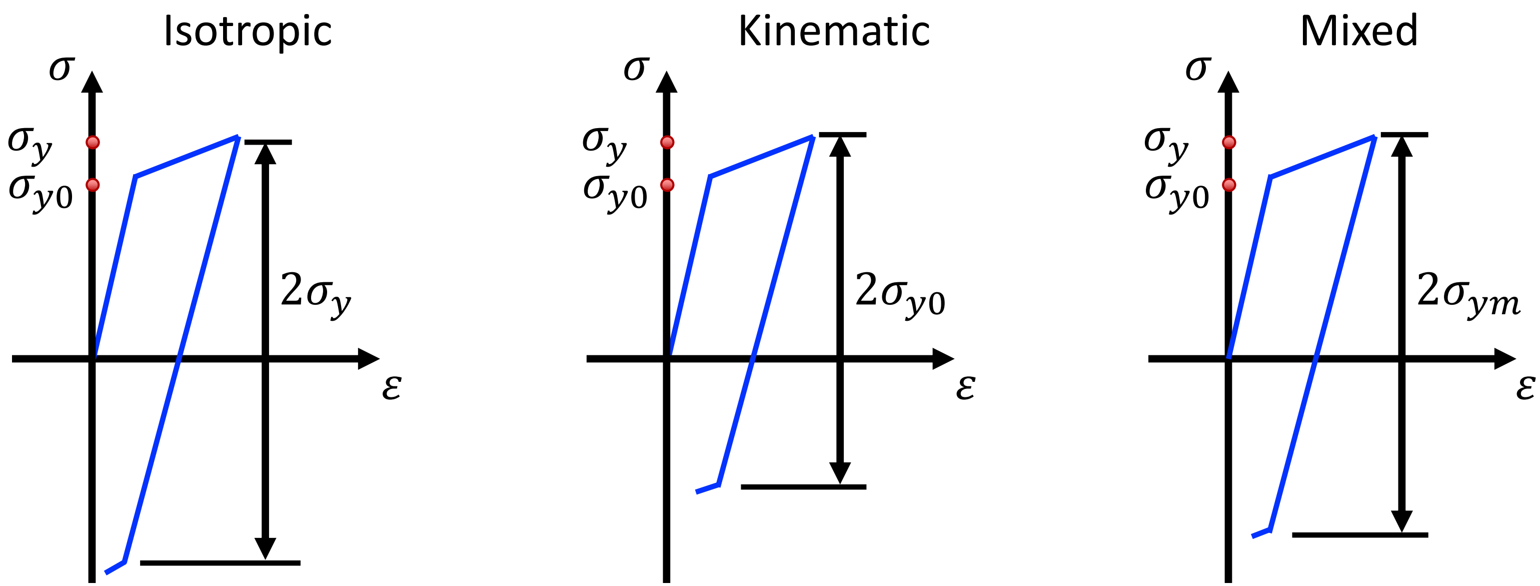
Plastic Hardening

Isotropic Hardening

- Uniform shift of yield surface
- Compresses at maximum of current yield stress σ_y

Kinematic Hardening

- Asymmetry between compressive and tensile yield stress
- Bauschinger's Effect
- Max compression of initial yield stress σ_{y0}



Cyclic Calibration

BCJ_MEM

- Rate and temperature-dependent elastoviscoplasticity model with isotropic damage
- Includes effects of recrystallization and grain growth

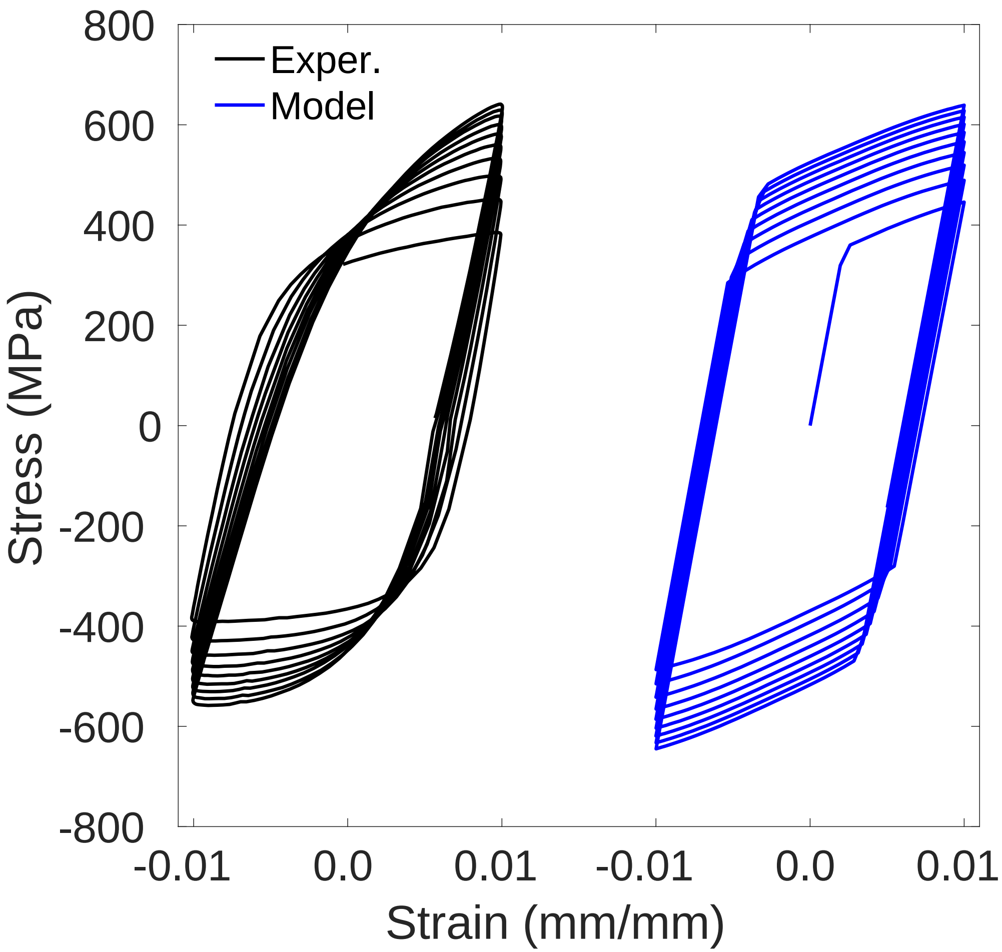
Plastic Strain

$$\dot{\epsilon}_p = f(\theta)\sinh\left\langle \frac{\sigma}{\kappa + Y(\theta)} - 1 \right\rangle \ ,$$

$$\dot{\kappa}(\kappa, H, R_{d1})$$

Parameters

$$E, \sigma_y, \nu, H_1, h_1, R_{d1}, r_{d1}$$



Cyclic Fit – 2

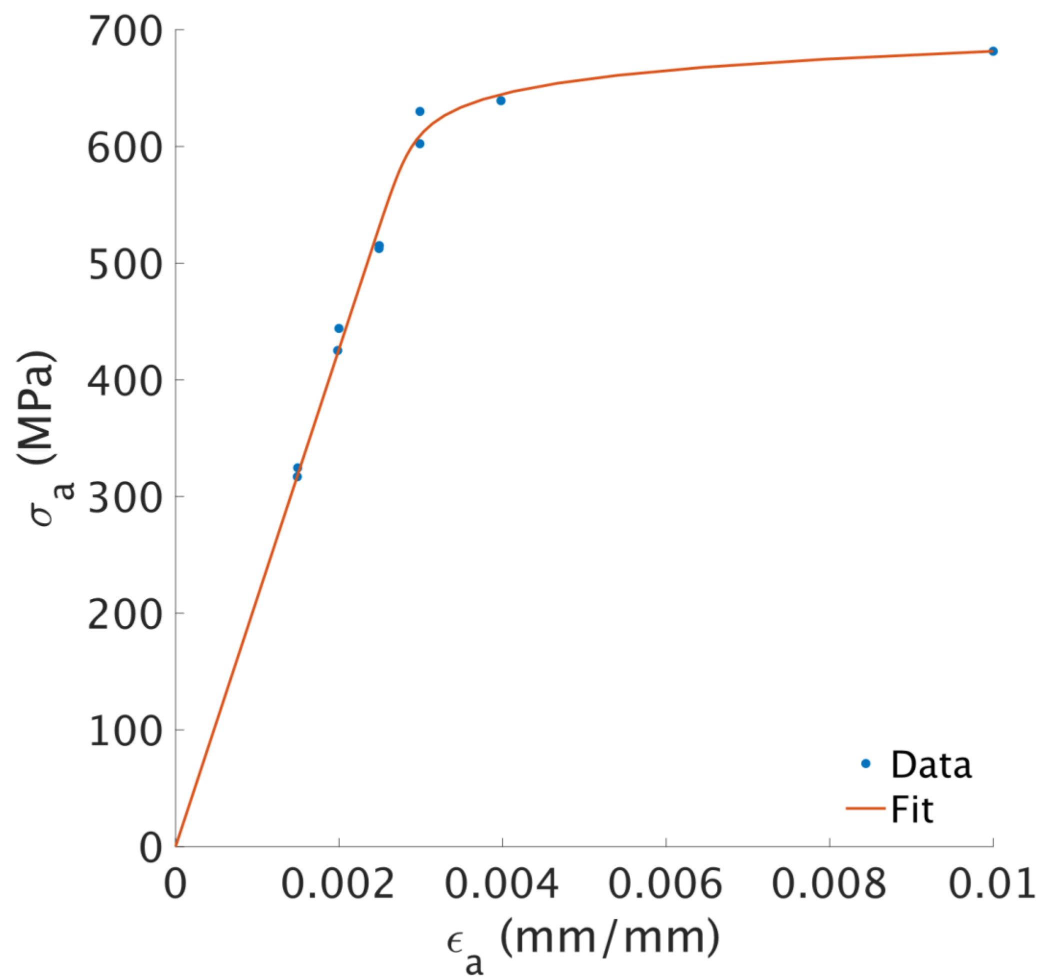
Ramberg-Osgood Curve

- Based on cyclic stress and strain amplitudes from near half the fatigue life
- Used to obtain n' and H' for analytical model

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{H'}\right)^{n'}$$

Parameter Values:

$$n' = 0.0112$$
$$H' = 7.13 \cdot 10^{10}\ \text{Pa}$$

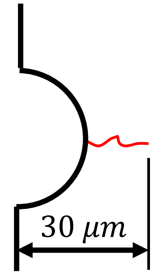


Multi-Stage Fatigue (MSF) Model

$$\boxed{N_{total} = N_{INC} + N_{SC} + N_{LC}}$$

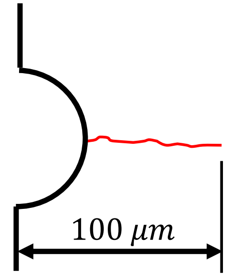
Incubation Cycles, N_{INC}:

$$\beta = \frac{\Delta\gamma_{max}^{p^*}}{2} = C_{INC} N_{INC}^{\alpha}$$



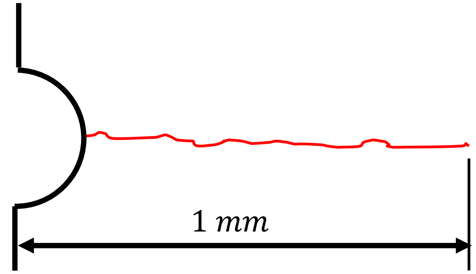
Small Crack Growth Cycles, N_{SC}:

$$\left(\frac{da}{dN}\right)_{SC} = \chi(\Delta CTOD - \Delta CTOD_{th})$$



Long Crack Growth Cycles:

$$\left(\frac{da}{dN}\right)_{LC} = \frac{C_i\left(\Delta K_{eff}\right)^{n_i}}{\left[1 - \left(\frac{K_{max}}{K_{Ic}}\right)^{q}\right]}$$

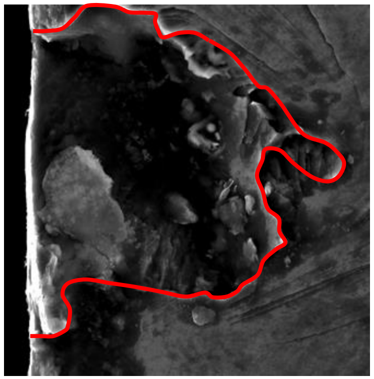


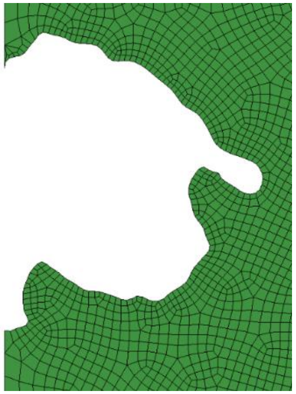
Source: McDowell et al., Eng Fract Mech, 2003

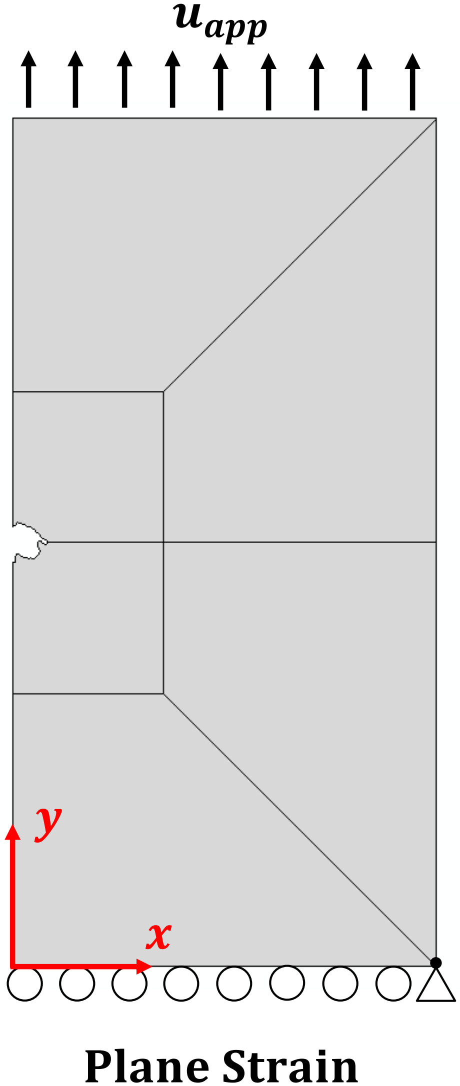
Xue et al., Eng Fract Mech, 2007

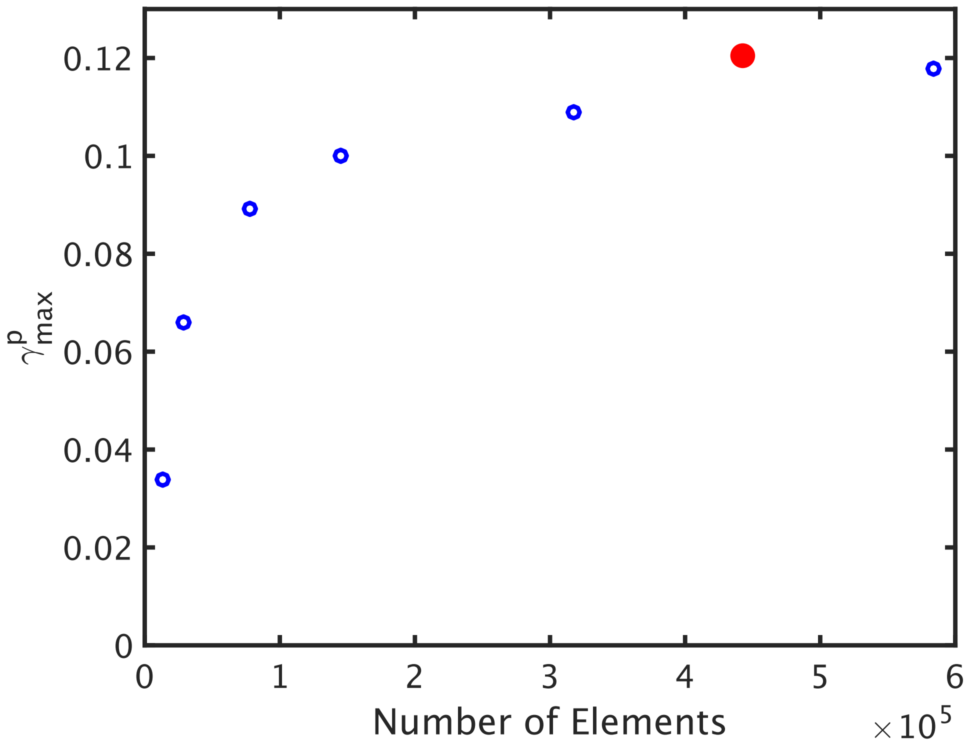
Xue et al., Acta Materialia, 2010

Finite Element Model – 2D

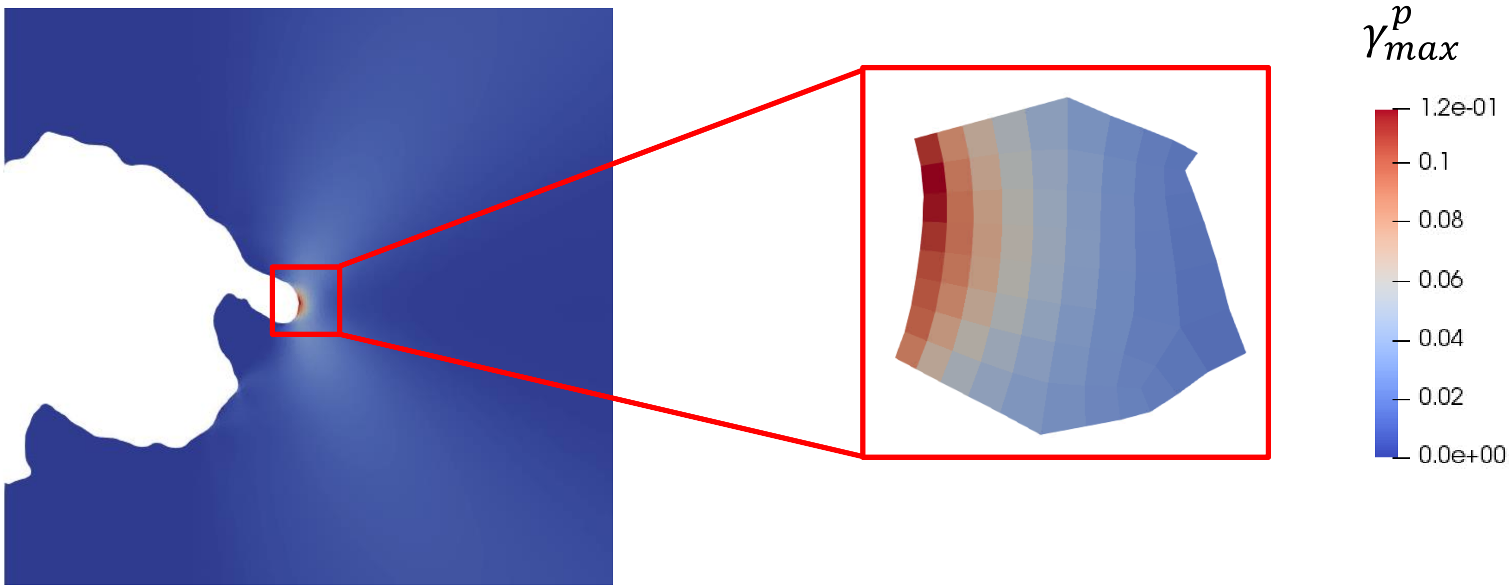








Average Maximum Plastic Shear Strain $\gamma_{max}^{P^*}$

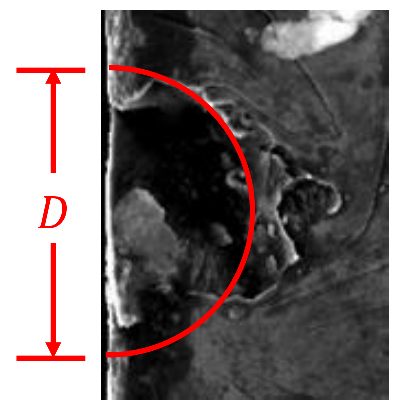


$$\gamma_{max}^{p^*} = \frac{1}{A_\beta} \int_{A_\beta} \gamma_{max}^{p} \, dA$$

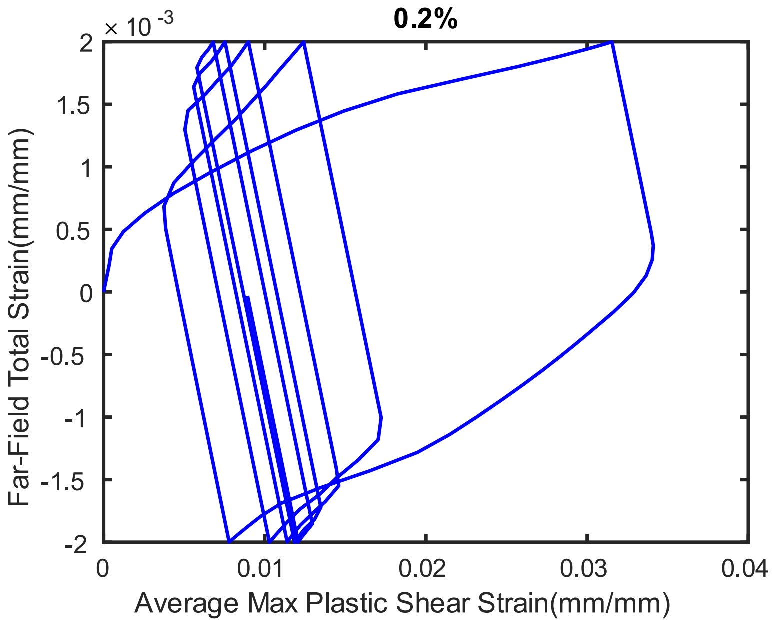
[Source: Xue et al., Eng. Fract. Mech., 2007]

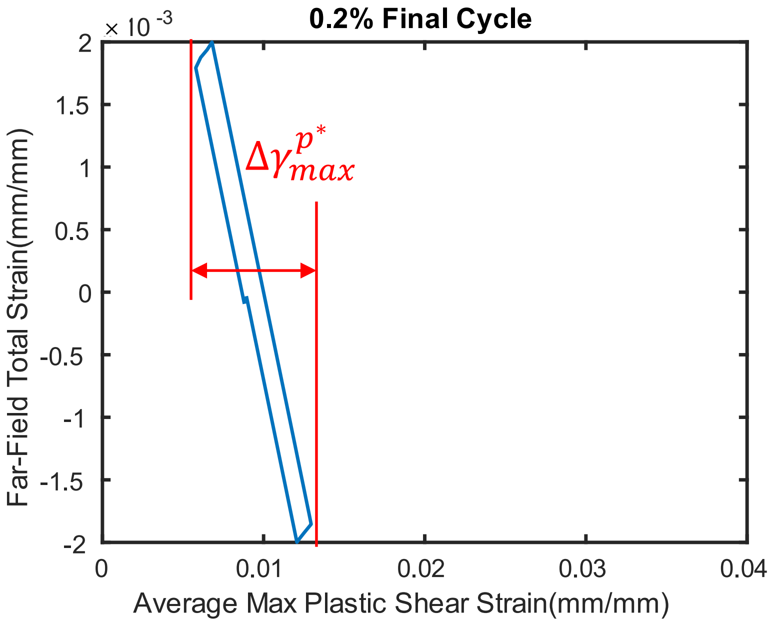
$$A_\beta = 0.012 D^2$$

[Source: Gall et al., Int J Fract, 2001]

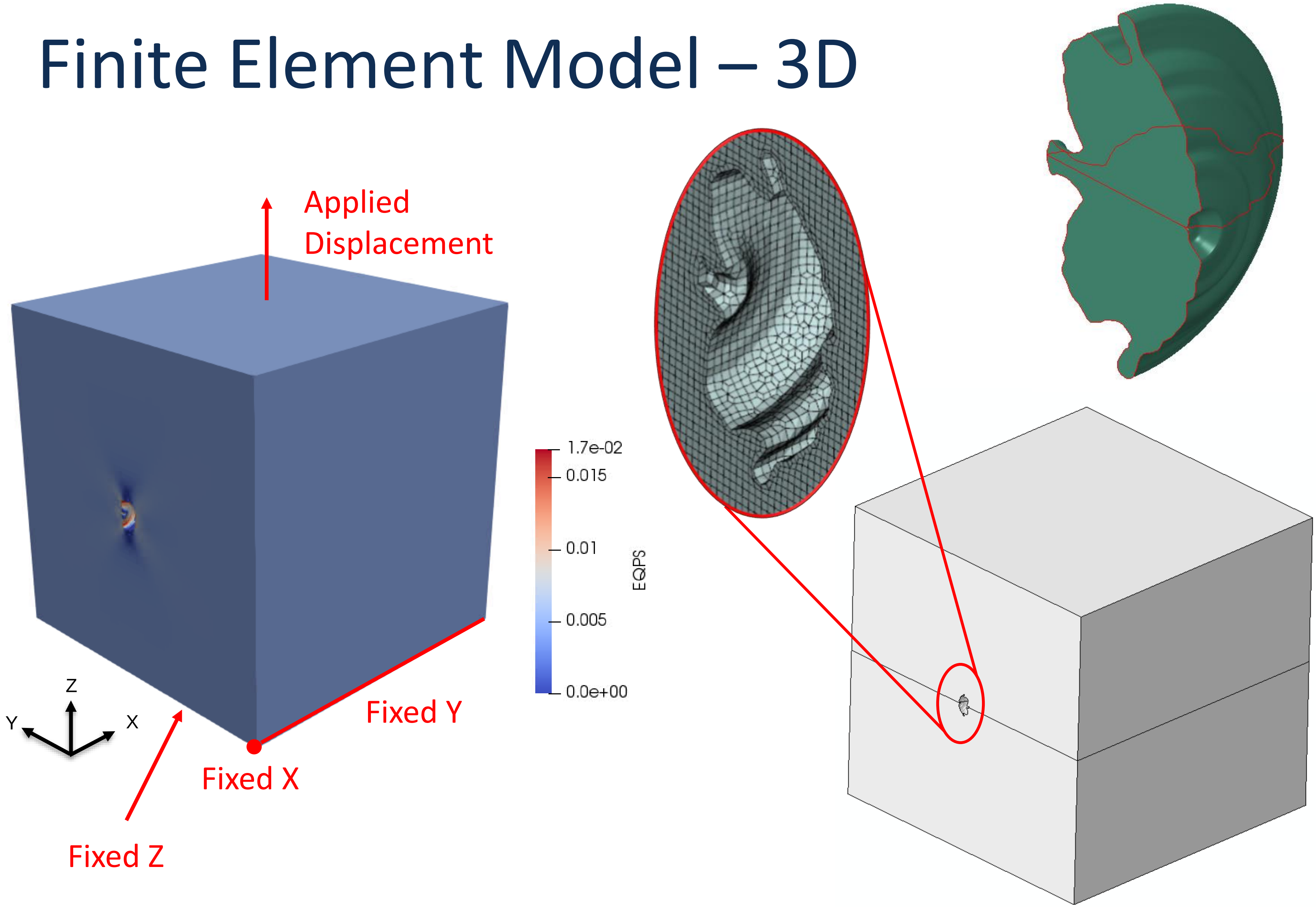


$\gamma_{max}^{p^*}$ versus ε_a



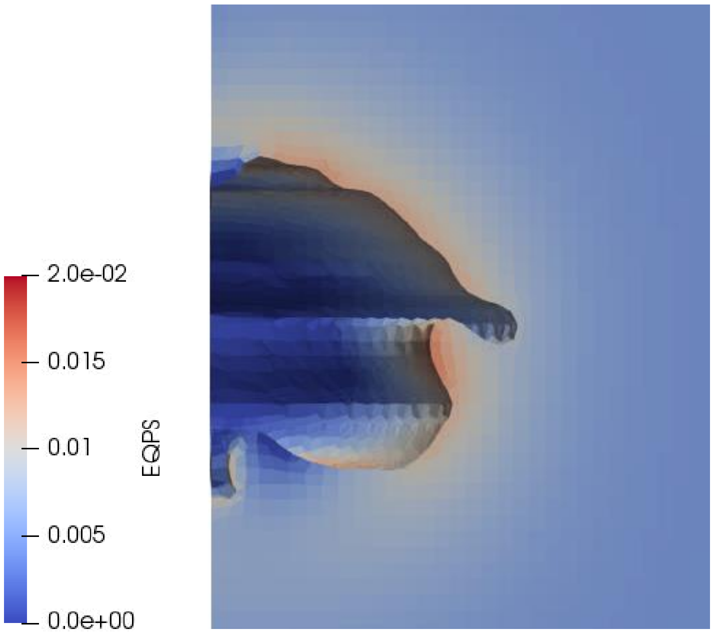


Finite Element Model – 3D

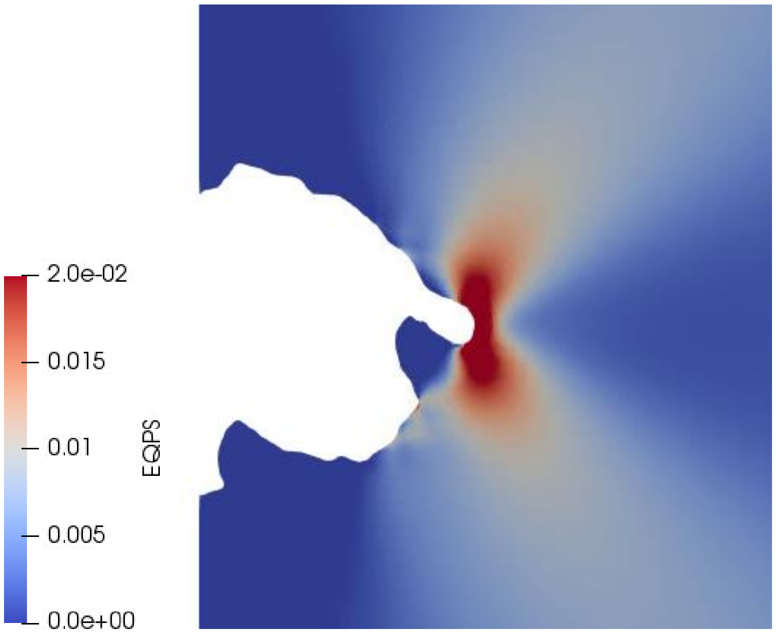


3D versus 2D

3D Model



2D Model

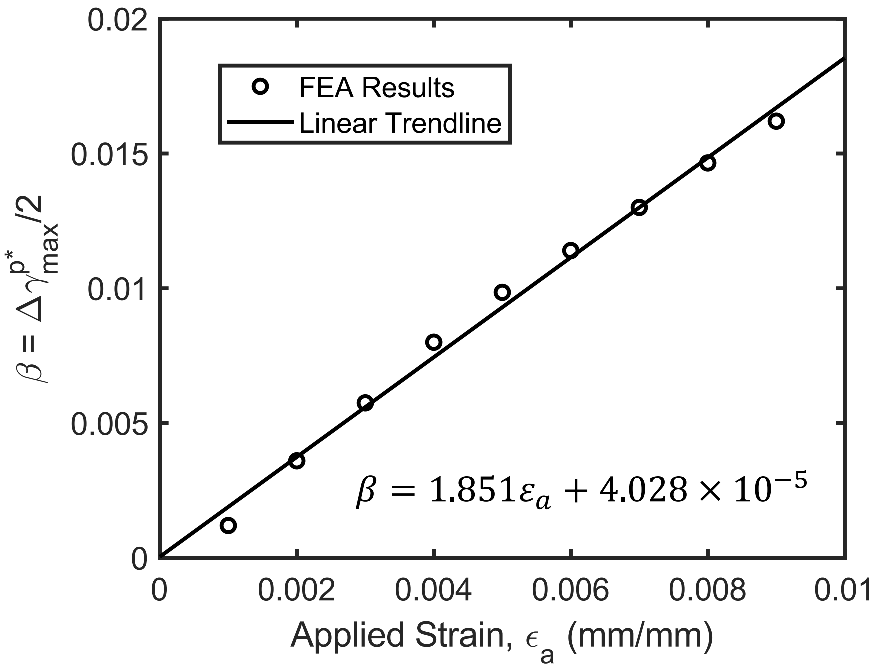


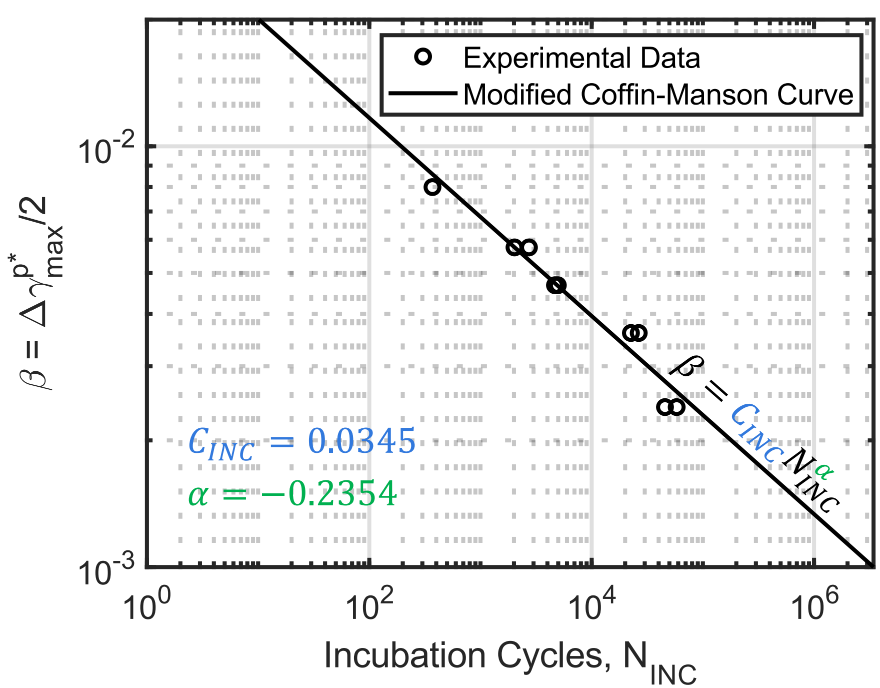
MSF Model

$$N_{total} = N_{INC} + N_{SC} + N_{LC}$$

Incubation Cycles, N_{INC}:

$$\beta = \frac{\Delta\gamma_{max}^{p^*}}{2} = C_{INC} N_{INC}^{\alpha}$$



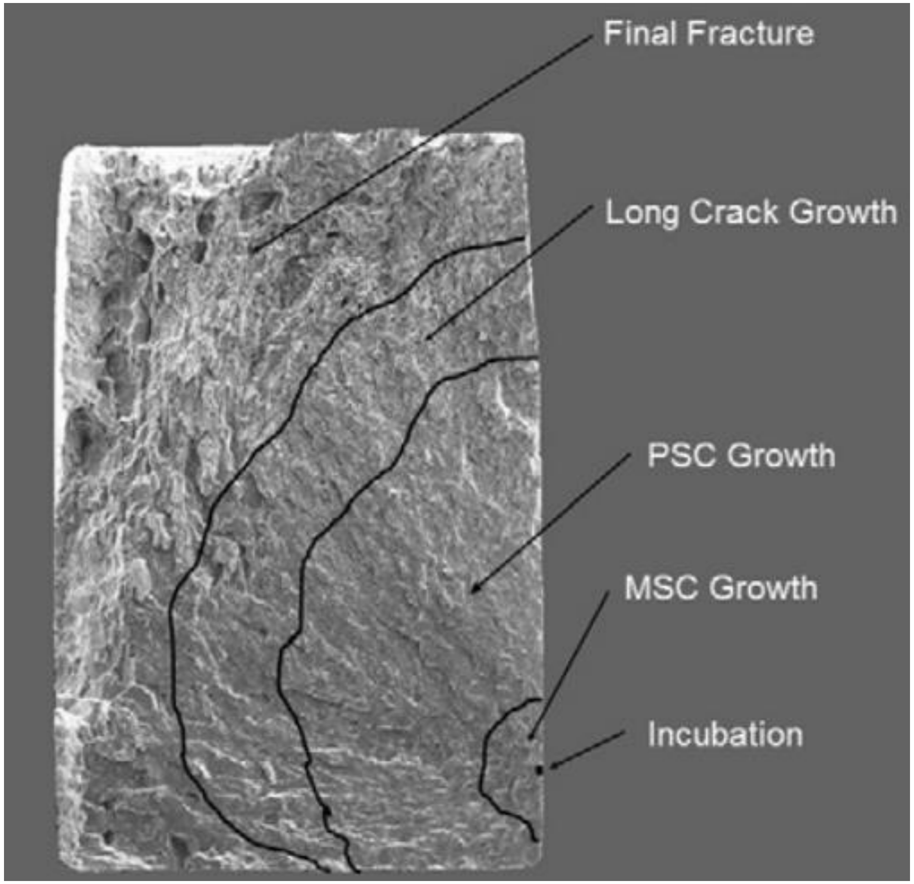


MSF Model

$$N_{total} = N_{INC} + N_{SC} + N_{LC}$$

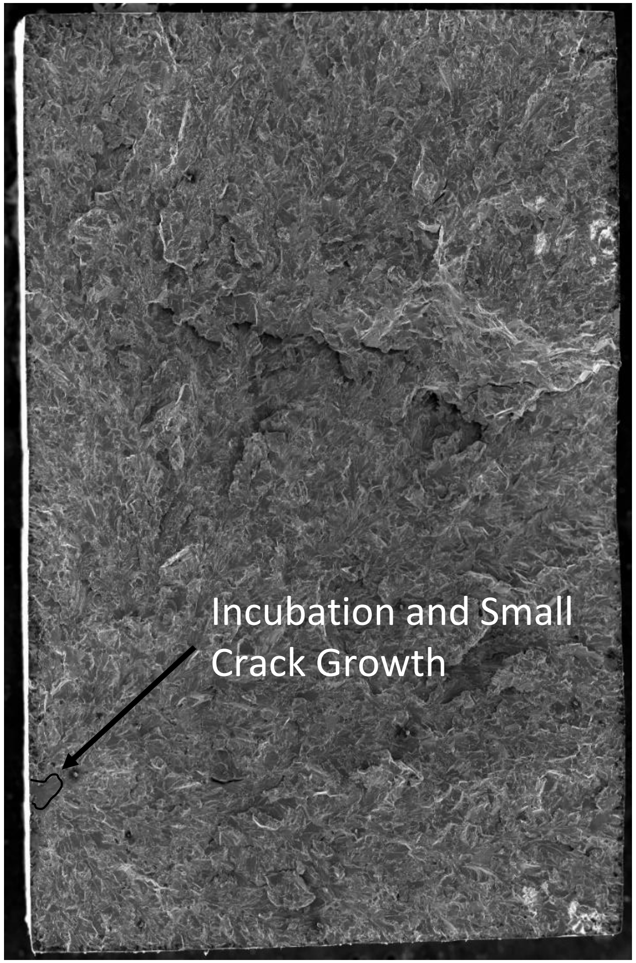
Incubation Cycles, N_{INC}:

Ti-6Al-4V



[Source: Torries et al., JOM, 2017]

Fe-Co-2V



Crack Propagation

- Crack propagation path determined using the e**X**tended **F**inite **E**lement **M**ethod (XFEM)

$$u^h(x) = \sum_{I \in N} N_I(x) \left[u_I + \overbrace{H(x) a_I}^{\text{Heaviside Enrichment Term}} + \overbrace{\sum_{\alpha=1}^{4} F_\alpha b_I^\alpha}^{\text{Crack Tip Enrichment Term}} \right]$$

[Source: Abaqus Analysis User's Guide, v6.14, Section 10.7]

- Initial crack: $0.01D \ = 0.542\ \mu m$
- Propagation modeled using LEFM
- Kink angle determined using *Maximum tangential stress criterion:*

$$\hat{\theta} = \cos^{-1}\left(\frac{3K_{II}^2 + \sqrt{K_I^4 + 8K_I^2 K_{II}^2}}{K_I^2 + 9K_{II}^2} \right)$$

[Source: Abaqus Theory Guide, v6.14, Section 2.16]

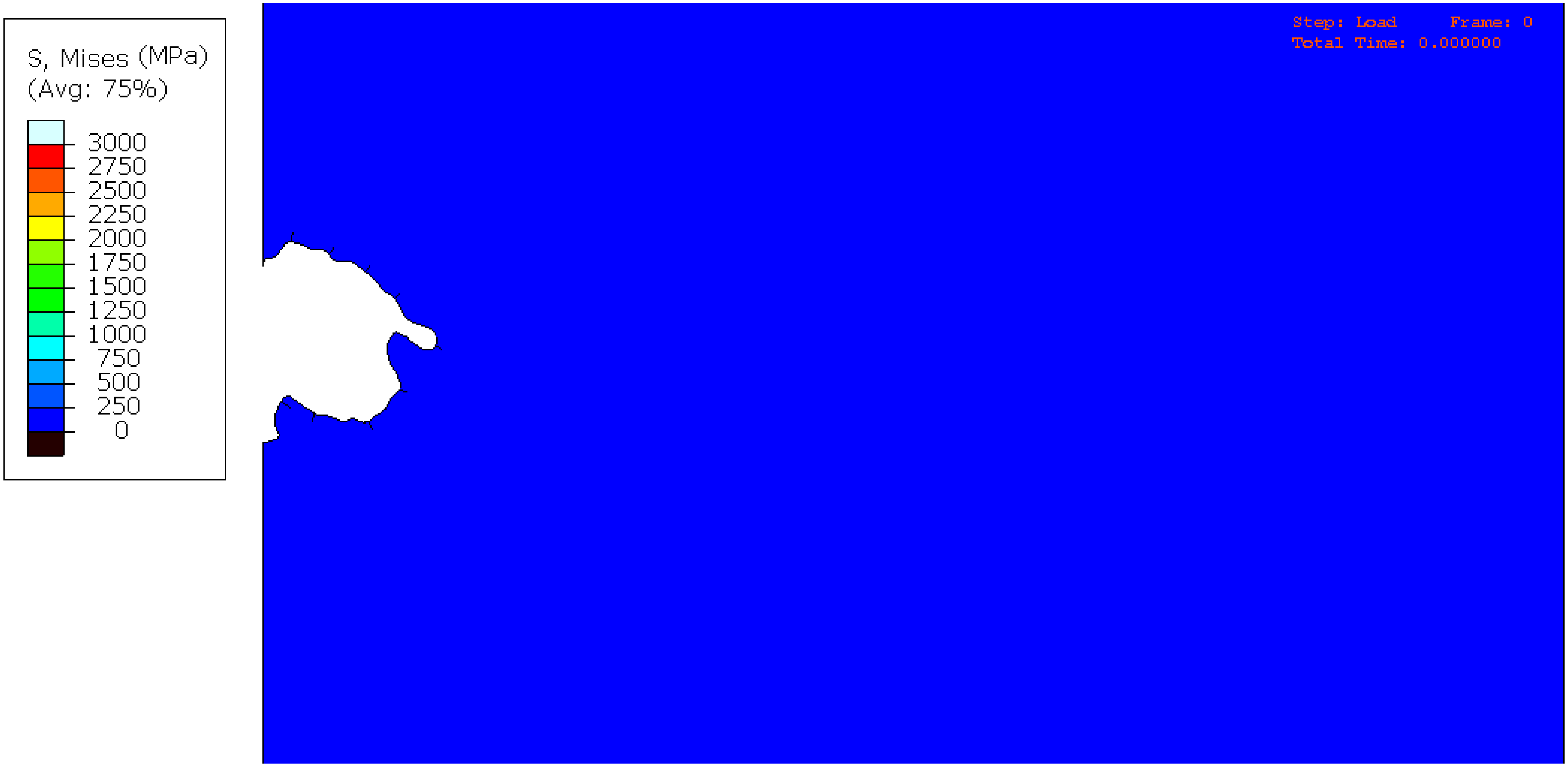
Crack Propagation

Applied Static Load

$\varepsilon_{app} = 0.5\%$

Linear Elastic Model

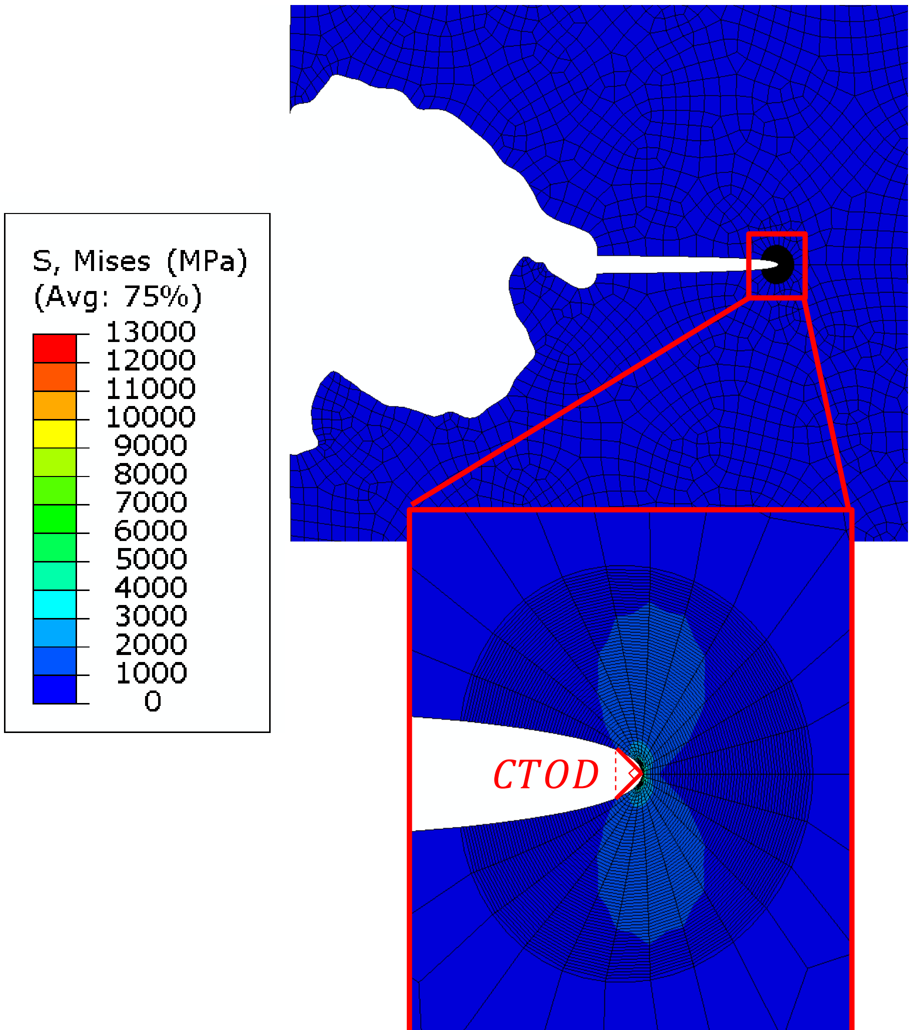
$E = 215\ MPa\ ,\ \nu = 0.335$

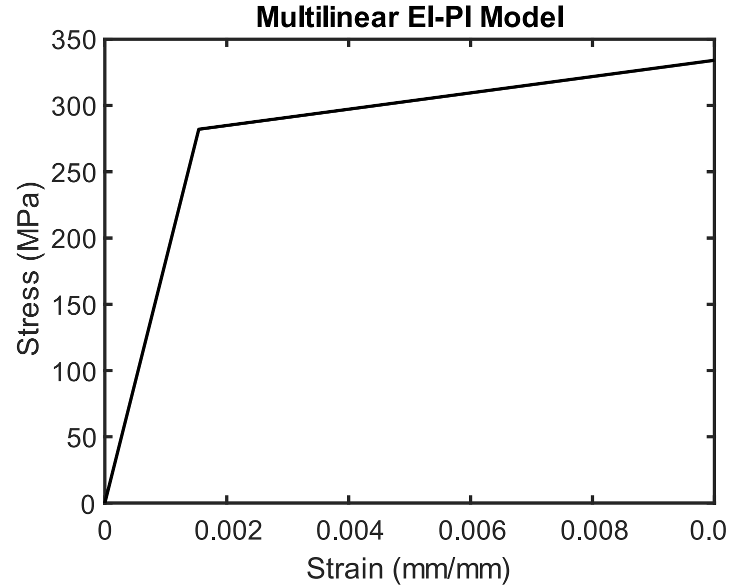


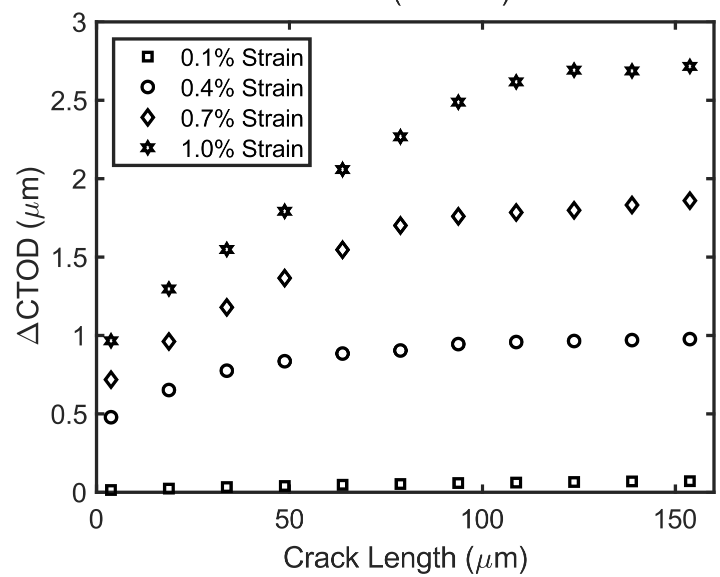
MSF Model

$$N_{total} = N_{INC} + N_{SC} + \cancelto{0}{N_{LC}}$$

Small Crack Growth Cycles, N_{SC}:



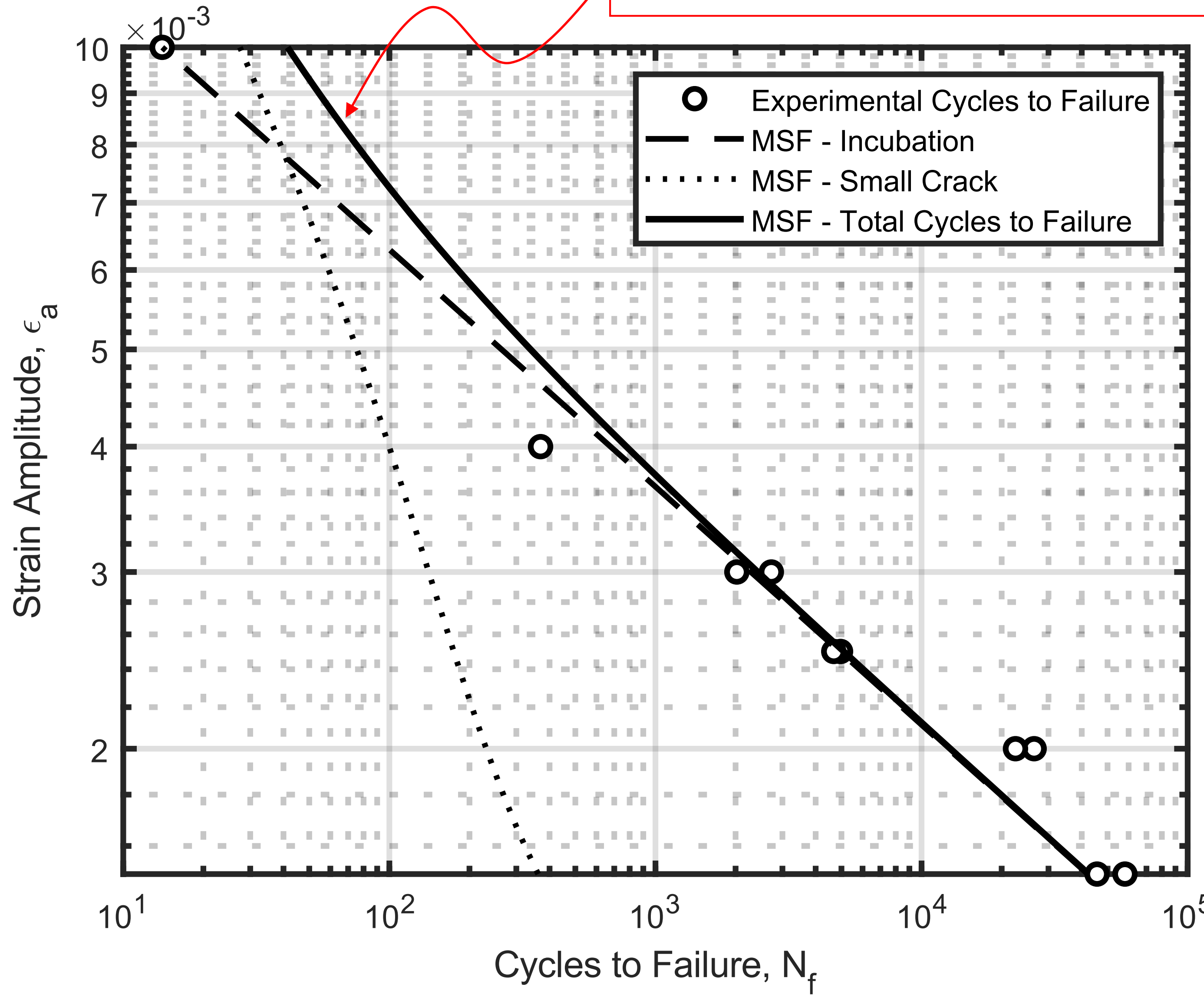




MSF Model

Larger discrepancy between MSF prediction and experimental data for larger strain amplitudes

→ **Incubation life assumption**



Conclusions & Future Work

Conclusions

- Fe-Co-2V Coffin-Manson parameters σ_f', b, ε_f', and c determined for the first time
- Micromechanical simulations were used to compute the nonlocal maximum plastic shear strain amplitude (β) and crack tip opening displacement (CTOD)
- A Multi-Stage Fatigue model was used to predict fatigue life with no parameter calibration

Future Work

- Upper and lower defect sizes to bound MSF model prediction
- Analysis of AM CT imagery
- More fatigue tests to populate strain-life curve

Acknowledgments

- This research was conducted at the 2018 Nonlinear Mechanics and Dynamics Research Institute hosted by Sandia National Laboratories and the University of New Mexico.

- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.